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**Effects of a Descending Lithospheric Slab on Yield
Estimates of Aleutian Nuclear Tests**

**Three Dimensional Structure of Subducted Lithospheric Slabs
Constraints from the Amplitudes and Waveforms of S Waves**

Vernon F. Cormier

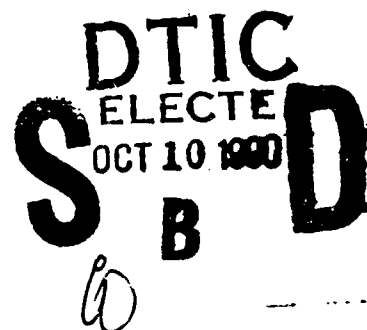
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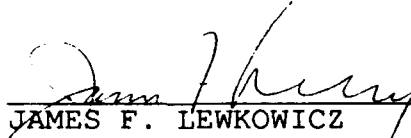



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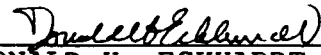
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This technical report has been reviewed and is approved for publication.


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Theoretical amplitudes and travel times were computed using vicinity ray tracing in several different types of descending slab models, including two new models proposed for the Aleutian slab by Boyd and Creager (1989). In agreement with a similar study of focusing and defocusing at the Nevada Test Site (Cormier, 1987), it was found that amplitudes do not correlate with travel times on a point for point basis, although broad regional anomalies in amplitudes correlate with broad regional anomalies in travel times. For a shallow focus source placed located to correspond to the relative locations of the Amchitka tests, a regional variation in P amplitudes was found that is similar to those found in the Study by Sleep (1973). Negative m_b residual of -0.2 to -0.3 units are predicted for in a broad azimuthal range on the dipping side of the slab. Lowest amplitudes are predicted at due North azimuths in the range of 70 to 90 great circle degrees. Smaller zones of positive m_b residual are predicted in the distance range 42 to 53 great circle range at due North azimuth, which is also a zone of P wave multipathing. Multipathing is also predicted PcP over small geographic regions perpendicular to the strike of the slab near 12 great circle degrees.

Many experiments were conducted in varying source location within and near slab structure. These demonstrate that multipathing is most easily induced if the source is located close to the high gradient zone defining the top of the slab.

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Abstract Continued

S and ScS amplitudes and travel times were also computed in these models, as part of a related study funded by NSF. For earthquakes located within slabs, it was assumed that regions of defocussing correspond to regions of maximum broadening and complexity in S waves. Slabs that thicken or have a reduced velocity contrast below, 650 km depth predict a different regional pattern of S and ScS waveform broadening compared to that predicted by slabs that penetrate the 650 km discontinuity for a long distance as a thin tabular structure. Data from the Kuril-Kamchatka slab are consistent with advective thickening or reduced velocity contrast below 650 km depth. The particular pattern of S and ScS waveform broadening in North America is more likely to be a consequence of a slab effect than an attenuation effect.

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TECHNICAL SUMMARY

The objective of this project is to determine the yield bias of underground nuclear tests induced by the presence of a high velocity descending slab beneath the test site. Specifically, the effect of the Aleutian slab is being investigated on the US underground tests Longshot, Milrow, and Cannikan. P wave seismograms will be synthesized using dynamic ray tracing and superposition of Gaussian beams in three-dimensional models of the Aleutian slab determined from P travel time delays. Focusing and defocusing and multipathing at teleseismic distances will be evaluated by comparison of observed with synthetic seismograms of the Aleutian tests.

Theoretical amplitudes and travel times were computed using vicinity ray tracing in several different types of descending slab models, including two new models proposed for the Aleutian slab by Boyd and Creager (1989). In agreement with a similar study of focusing and defocusing at the Nevada Test Site (Cormier, 1987), it was found that amplitudes do not correlate with travel times on a point for point basis, although broad regional anomalies in amplitudes correlate with broad regional anomalies in travel times. For a shallow focus source placed located to correspond to the relative locations of the Amchitka tests, a regional variation in P amplitudes was found that is similar to those found in the Study by Sleep (1973). Negative m_b residuals of -.2 to -.3 units are predicted for in a broad azimuthal range on the dipping side of the slab. Lowest amplitudes are predicted at due North azimuths in the range of 70 to 90 great circle degrees. Smaller zones of positive m_b residual are predicted in the distance range 42 to 53 great circle range at due North azimuth, which is also a zone of P wave multipathing. Multipathing is also predicted PcP over small geographic regions perpendicular to the strike of the slab near 12 great circle degrees.

Many experiments were conducted in varying source location within and near slab structure. These demonstrate that multipathing is most easily induced if the source is located close to the high gradient zone defining the top of the slab.

S and ScS amplitudes and travel times were also computed in these models, as part of a related study funded by NSF. For earthquakes located within slabs, it was assumed that regions of defocussing correspond to regions of

maximum broadening and complexity in S waves. Slabs that thicken or have a reduced velocity contrast below 650 km depth predict a different regional pattern of S and ScS waveform broadening compared to that predicted by slabs that penetrate the 650 km discontinuity for a long distance as a thin tabular structure. Data from the Kuril-Kamchatka slab are consistent with advective thickening or reduced velocity contrast below 650 km depth. The particular pattern of S and ScS waveform broadening in North America is more likely to be a consequence of a slab effect than an attenuation effect.

THEORETICAL AMPLITUDE ANOMALIES OF ALEUTIAN NUCLEAR TESTS

Theoretical amplitudes and travel times were computed using vicinity ray tracing (Kim and Cormier, 1990) in the long slab model of Body and Creager (1989) for the Aleutian slab for source positions corresponding to underground nuclear tests in the island ridge adjacent to the slab. In constructing the model shown in Figure 1, the raw thermal model was obtained from Creager (personal communication) and converted to a P velocity model by assuming the temperature derivative of P velocity used by Boyd and Creager, $dV_P/dT = 0.5 \text{ ms}^{-1} \text{ K}^{-1}$. Details of the amplitude calculation are described in the section following this one, which also describes experiments calculating slab focusing and defocusing and in several different types of slab models and source positions within the slab.

Figure 2 shows P and PcP rays predicted for Amchitka tests in the Boyd and Creager model. The rays are shown for a 2-D cross section, perpendicular to the strike of the slab. Multipathing can be observed at the great circle distances 42° to 53° for P waves and around 12° for PcP waves.

Amplitude and travel times were calculated in models with and without the slab using PREM as a reference model. P amplitude anomalies are shown in figure 3, contoured in m_b residuals. A geographic plotting convention is used rather than a focal sphere plot. The epicenter is at the center of the sphere, the inner circle corresponds to the area at distances less than or equal to 35° , the outer circle corresponds to core grazing distances.

The amplitude variations in Figure 3 roughly agree with the data shown in Figure 10 of Sleep's (1973) study. Highest amplitudes occur around an annular region at 42° to 53° . Low amplitudes occur at longer distances outside this ring, nearly everywhere on the dipping side of the slab. Peak m_b residuals are bounded by 0.3 m_b units. The lowest amplitudes occur at azimuths due North, perpendicular to the strike of the slab, at ranges exceeding 53° . This is the region in which evidence of pulse broadening has been reported in long period and broadband waveforms from shallow focus Aleutian events (Engdahl et al., 1989). Since this is a region of strong defocusing (-0.3 m_b residual), the pulse broadening may likely be caused by slab diffraction.

Large anomalies in PcP amplitudes of +0.6 log amplitude units occur in two symmetric geographic regions at 12° range (Figure 4). Multipathing of

PcP is predicted to occur in these regions. The largest amplitude multipath was chosen for contouring. Core reflected phases such as PcP and ScS are particularly sensitive to steeply dipping slab structures and can be used as effective tools in discriminating between possible deep slab structures.

Predicted travel time anomalies of the P waves from Aleutian tests are shown in Figure 5. Travel time anomalies are uniformly negative due to fact that all rays interact to some extent with the high velocity slab structure. The fast travel time correlate with low amplitudes in a broad regional sense, but many exceptions to the broad correlation can be seen in a comparison with the amplitude anomalies shown in Figure 3.

In summary, forward modeling in recently proposed models of the Aleutian slab is generally consistent with the predictions obtained in earlier studies by Davies and Julian (1972) and Sleep (1973). In continued work in this project, we will make an effort to include additional digital waveform data not available to these earlier studies in order to confirm both their results as well as to investigate the effect of the Aleutian slab on P waveform broadening and complexity.

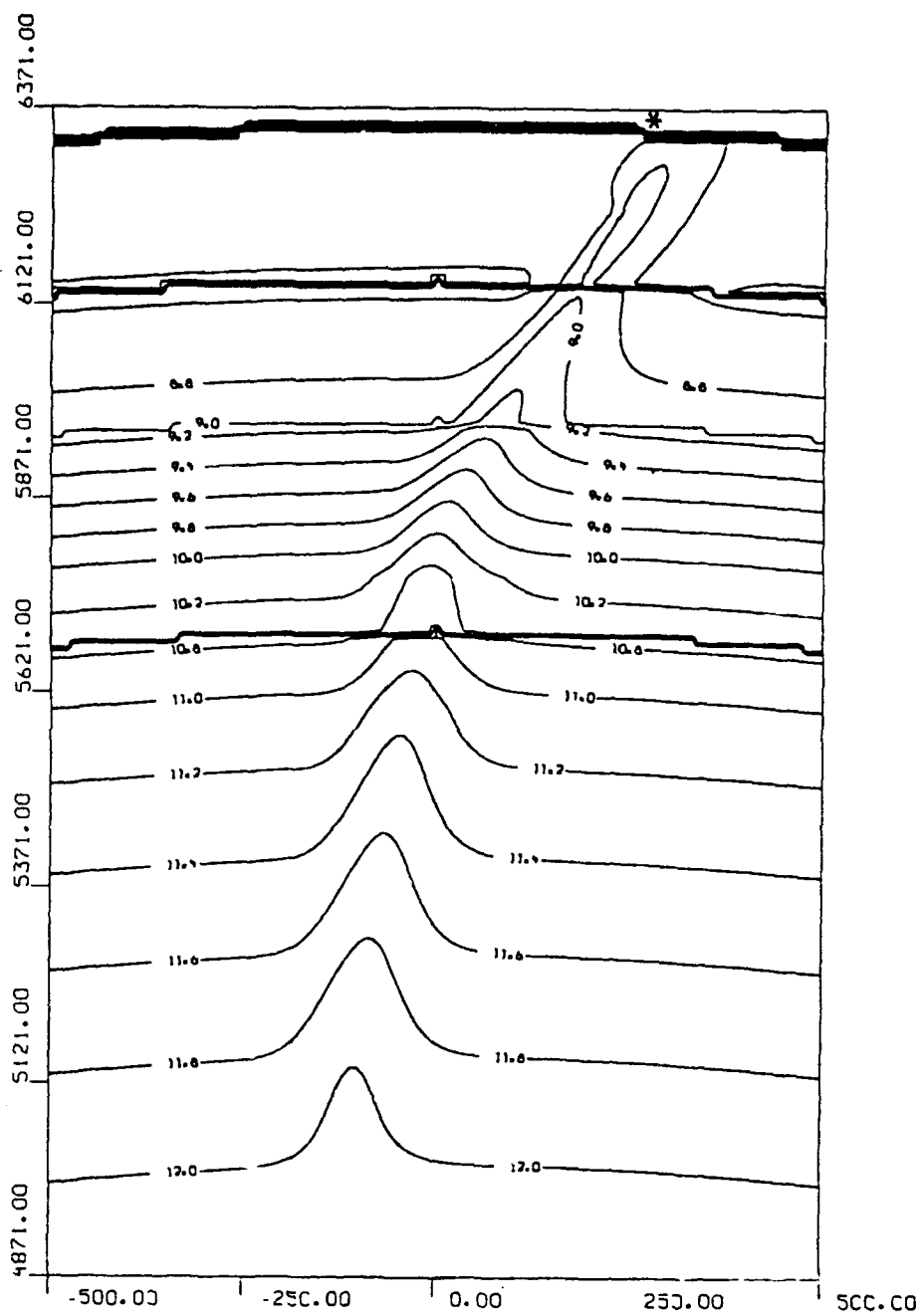


Figure 1: P velocity model of the Aleutian slab in the vicinity of the Amchitka test site determined by Boyd and Creager (1989)

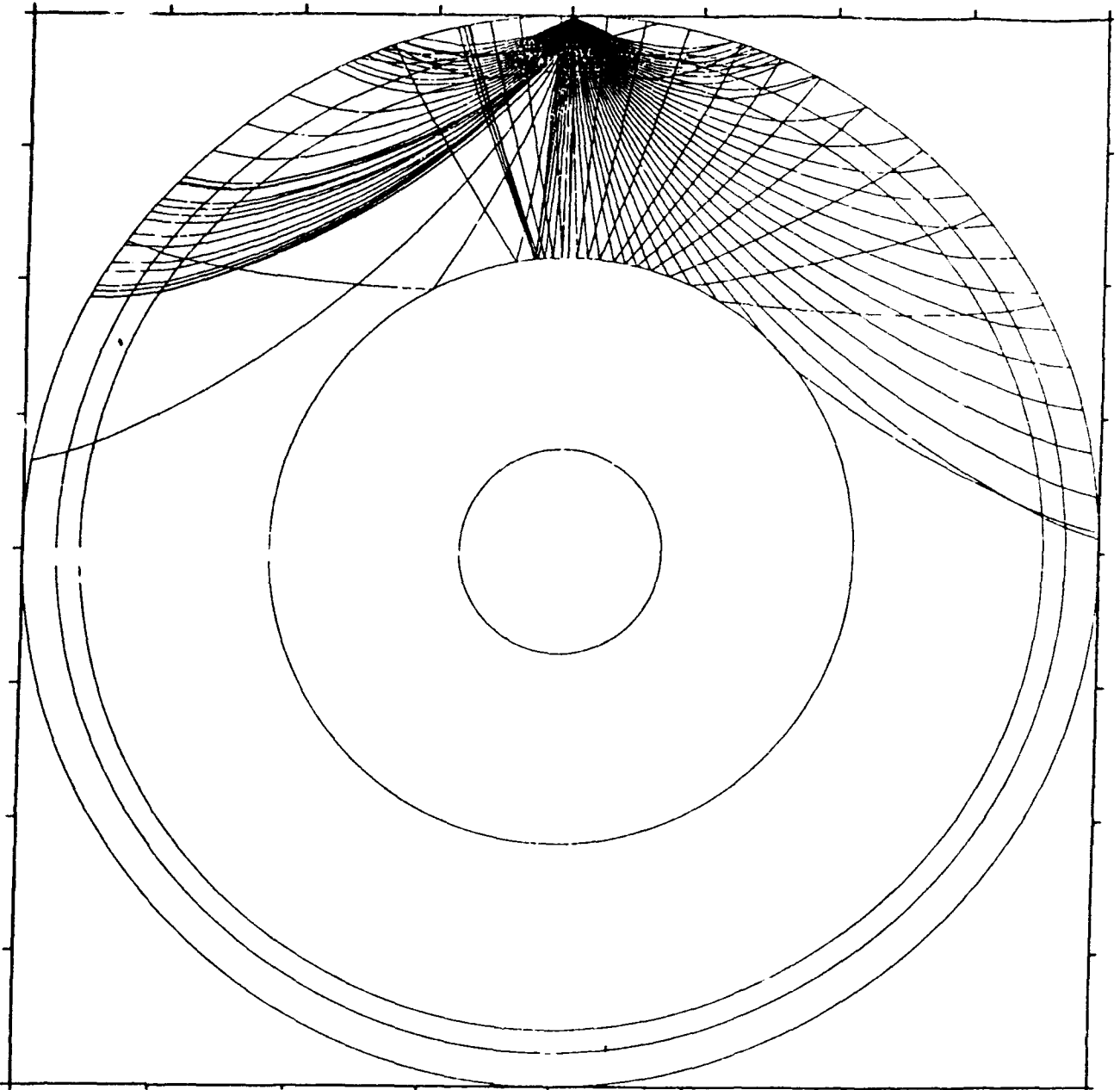


Figure 2: P and PcP ray trajectories in a plane perpendicular to the strike of the Aleutian slab model shown in Figure 1.

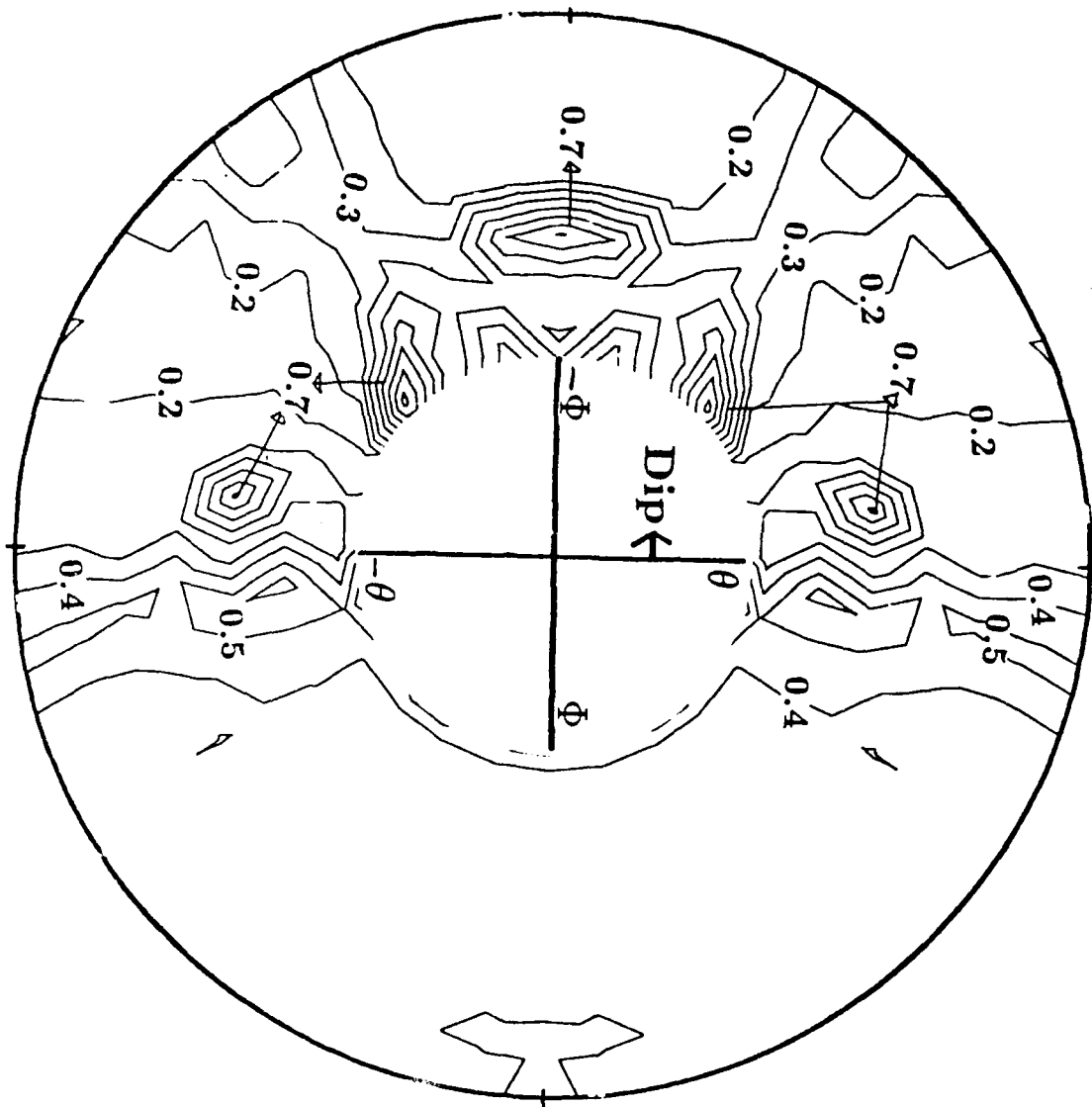


Figure 3: Predicted P amplitude anomalies for a source located as shown in the model shown in Figure 1. Anomalies are contoured in m_b units. An equal area geographic projection has been used, with the inner radius corresponding to 40° distance and the outer radius to 90° degrees distance.

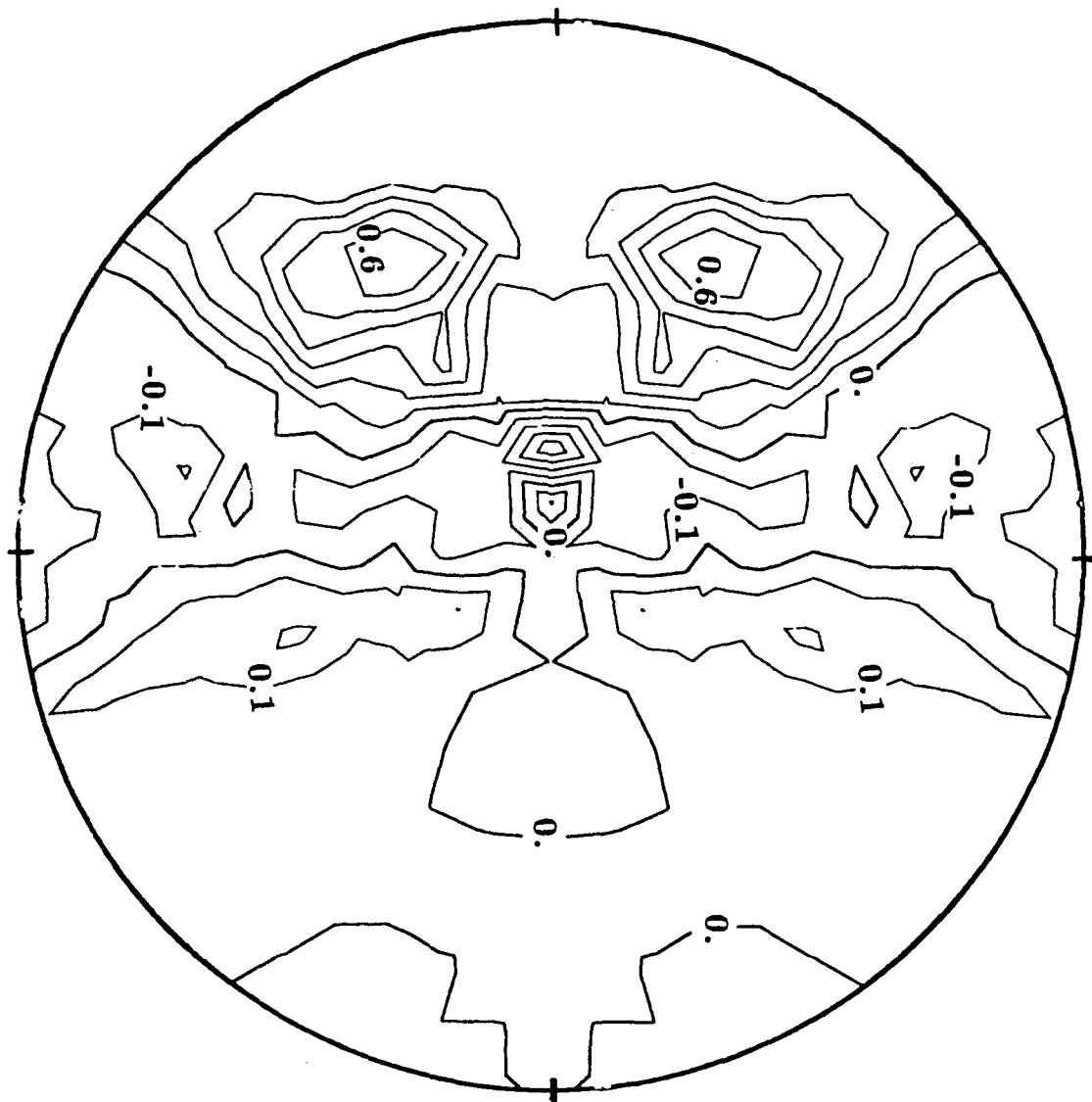


Figure 4: Predicted PcP amplitude anomalies for a source located as shown in the model shown in Figure 1. Plotting is an equal area geographic projection with the outer radius corresponding to 90° degrees distance.

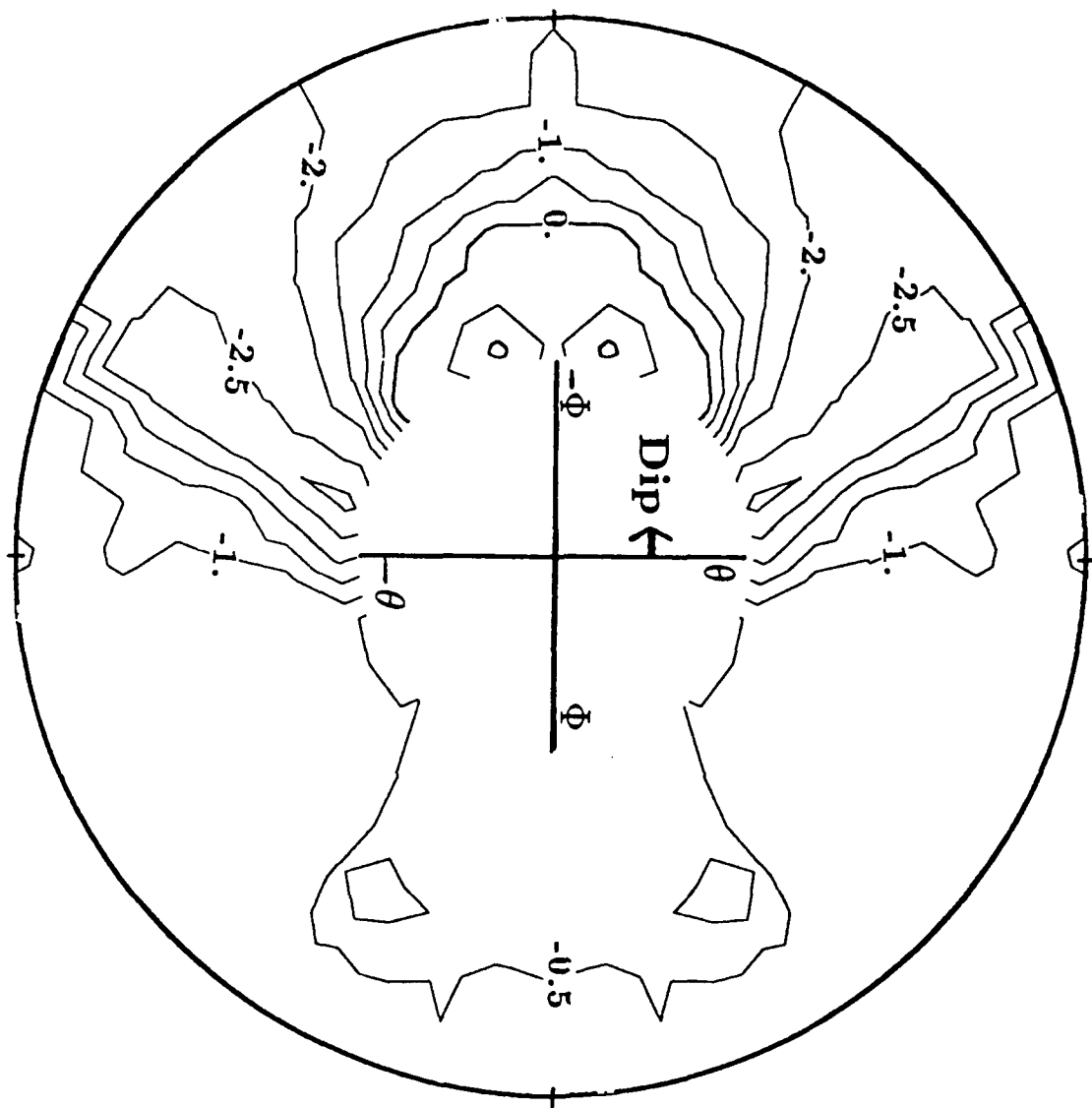


Figure 5: Predicted P travel time anomalies in seconds for a source located as shown in the model in Figure 1. Anomalies are calculated relative to PREM.

Three-dimensional Modeling of Subducted Lithospheric
Slabs from the Amplitudes and Waveforms of S Waves

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Abstract

A modified form of dynamic ray tracing is used to predict travel times, geometric spreading, and waveform distortions of S waves radiated by deep focus earthquakes located in several different thermal models of slab structure proposed below 650 km depth. By assuming that the peak displacement amplitudes calculated from frequency independent ray theory are the same as those calculated from finite difference studies, the regional dependence of waveform broadening due to the frequency dependent phenomenon of slab diffraction may be predicted. Using this hypothesis the following are predicted:

(1) Steeply dipping slabs that penetrate the 650 km discontinuity, with little advective thickening and a strong temperature contrast from the surrounding mantle, produce fast travel times, low amplitudes, and slab diffraction of primarily ScS waveforms in nearly a 180 degree azimuthal sector on the dipping side of the slab. These effects are much smaller in S waves except along azimuths close to the strike of the slab.

(2) Slabs that advectively thicken and/or suffer a strong change in temperature contrast below 650 km depth predict fast travel times, low amplitudes, and waveform broadening in S but not ScS waves along azimuths principally along the strike of the slab. The S anomalies increase as the great circle range decreases below 60 degrees.

(3) S and ScS waveforms and travel times observed from deep focus earthquakes occurring within the Kuril-Kamchatka slab are more consistent with (2) than (1). This suggests that while a slab structure or thermal anomaly likely exists below 650 km depth, it experiences some advective thickening below this depth.

Introduction

The travel times of P and S waves from deep focus earthquakes have suggested that slabs may penetrate into the deep mantle of the Earth below 650 km depth. This depth is close to the deepest recorded earthquakes and also coincides with a rapid, probably discontinuous increase in seismic velocities and density.

It is important to determine whether the cutoff in seismicity and the changes in physical properties of the mantle at 650 km depth correspond to a solid-solid phase change and/or a compositional change in the mantle at this depth. If it is a compositional change or if the change in physical properties greatly reduces the negative buoyancy of the slab, then the likely mode of mantle convection would be two-layered rather than a single layer between the asthenosphere and core-mantle boundary. In this case, one would expect the slab not to penetrate very far beyond 650 km depth and to suffer some deformation, advective thickening, or rapid diminution and assimilation into the lower mantle below this depth. If this not the case, the slab may penetrate below 650 km depth with little change in in shape.

To answer these questions, we conducted a series of experiments on the effects of several proposed slab structures in the lower mantle on the waveforms and amplitudes of seismic body waves. It is shown that the waveforms and amplitudes of body waves can provide constraints on slab structure independent of travel times. The results of these tests demonstrate that combined waveform and travel time data from deep focus earthquakes may be able to determine the nature of slab deformation near 650 km depth and thereby constrain the types of changes in physical properties of the mantle at this depth.

Calculation of Slab Effects on Waveforms

Previous Studies

General. Slab structure can affect waveforms and amplitudes as well as the travel times of body waves radiated by deep focus earthquakes. The waveform effects include focusing and defocusing, multipathing, and diffraction (Sleep, 1973; Davies and Julian, 1972; Vidale, 1987; Cormier, 1989; Silver and Chan, 1986; Engdahl et al., 1989; Vidale and Garcia-Lopez, 1988; Weber, 1990).

Gaussian beams. In an earlier study (Cormier, 1989), the frequency dependent effects of slab diffraction were approximately modeled using a superposition of Gaussian

beams. In a three-dimensional model, the beam superposition required several hundred dynamically traced rays to synthesize each body wave. To better approximate the Fresnel zone responsible for slab diffraction, beams were shot reciprocally from receiver to source rather than from the source to the receiver. An earth flattening transformation was assumed to simplify the conversion between the Cartesian coordinates, in which the model was specified, and the ray centered coordinates, in which the dynamic ray tracing equations were specified.

The limitation of the Gaussian beam method in the synthesis of the frequency dependent slab diffraction is associated more with its inability to properly describe the frequency dependence of the Fresnel zone in the source region than with any failure of the asymptotic and paraxial approximations in the spatially varying slab structure. Most of the proposed thermal models of slab structure are sufficiently smooth and slowly varying for both asymptotic and paraxial approximations to remain accurate in the frequency band of interest to broad band body waves. If beams are shot from the source to the receiver, their superposition simply reproduces the predictions of geometric ray theory, i.e., the frequency independent amplitudes determined from geometric spreading. This is because the class of ray paths included in the superposition excludes rays at grazing incidence to the high gradient zones defining the boundaries of the slab.

It is possible, however, to include these rays by shooting beams reciprocally from the receiver to the source. In this case, the superposition will produce broadened waveforms due to slab diffraction in a large geographic region on the dipping side of the slab. The waveform broadening vanishes as beam widths are decreased and/or the frequency band of synthesis increases.

The slab problem demonstrates that Gaussian beams satisfy reciprocity only in the limit of geometric ray theory in which beam widths become much narrower than those needed to describe properly the frequency dependence of the Fresnel zone responsible for slab diffraction. For these reasons, the Cormier (1989) study employed a reciprocal source-receiver geometry and calibrated beam parameters by comparing waveforms synthesized by beam superposition in three-dimensions with waveforms synthesized by the finite difference method in two-dimensions (Vidale, 1987; Witte, 1987). Because the beam method fails reciprocity and is limited in its ability to describe properly the Fresnel zone in the vicinity of the source region, it was deemed inappropriate at this time to apply superposition of Gaussian beams in a more comprehensive study of slab diffraction. Many valuable insights on slab structure, however, can be gained by a study of the focusing and defocusing effects of slabs predicted by simple geometric ray theory, and these

effects can be accurately calculated by dynamic ray tracing and conventional beam superposition.

This Study

Amplitudes and waveform complexity due to multipathing. In the present study, a modified form of dynamic ray tracing is applied in a spherical model to calculate peak amplitudes, travel times, and $\pi/2$ phase shifts induced by slab structure. Although this approach ignores frequency dependent effects and overestimates peak amplitudes in the vicinity of caustics, it allows a rapid reconnaissance of the principal effects of slab structures while including some advances over similar earlier studies. The estimates of geometric spreading should be more accurate in principal than those obtained in studies that calculate spreading from the differential area of closely spaced rays. The $\pi/2$ phase shifts introduced when rays touch a caustic surface produce significant waveform distortion. Calculation of these phase shifts can aid in identifying which slab models produce unrealistic waveform distortions.

Waveform complexity due to slab diffraction. In this approach it is worthwhile to compare the regional dependence of amplitudes obtained by dynamic ray tracing with the regional dependence of waveform complexity and pulse broadening obtained by methods that include the frequency

dependent effects of slab diffraction. The results of such a comparison can be used to predict the regional dependence of slab waveform effects simply on the basis of peak amplitudes. An examination of Figure 1 shows how such a prediction of slab waveform effects can be made. Note that the degree of pulse broadening and slab diffraction correlates with both amplitude and travel time anomaly. The fastest travel time and smallest amplitudes correlate with the greatest amount of pulse broadening. A 50% reduction in amplitude will begin to be associated with discernible pulse broadening. At a 70% or more reduction in amplitude, a large amount of broadening begins to be observed, often with a secondary diffracted pulse.

Calculations. The modified form of dynamic ray tracing used in this study is termed vicinity ray tracing (Kim and Cormier, 1990). The locus of a ray nearby a reference ray is calculated by integrating four differential equations for the ray centered coordinates (q_1, q_2) of the nearby ray measured from the reference ray and the angular differences (η_1, η_2) between the tangent to the reference ray and the tangent to the vicinity ray (Figure 2). These equations are

$$\frac{dq_1}{ds} = \frac{h_1^2 v}{v_1} \sin \eta_1$$

$$\frac{dq_2}{ds} = \frac{h_2^2 v}{v_2} \sin \eta_2$$

(1)

$$\begin{aligned} \frac{d\eta_1}{ds} &= \frac{h_1 v_{1,s}}{v_1} \tan \eta_1 + C \frac{v_1}{\cos \eta_1} \\ \frac{d\eta_2}{ds} &= \frac{h_2 v_{2,s}}{v_2} \tan \eta_2 + \frac{v_1}{\cos \eta_1} \end{aligned}$$

where

$$C = \frac{v, q_1}{h_1 v^2} - \frac{v v_{1,q_1} h_1^2}{v_1^3}$$

$$D = \frac{v, q_2}{h_2 v^2} - \frac{v v_{2,q_2} h_2^2}{v_2^3}$$

$$h_1 = 1 + \frac{v, 1}{v} q_1$$

$$h_2 = 1 + \frac{v, 2}{v} q_2$$

$$v = v(s, 0, 0)$$

$$v_1 = v(s, q_1, 0)$$

$$v_2 = v(s, 0, q_2)$$

Lower case v denotes velocity along the central ray and upper case V denotes velocity along a vicinity ray. Equations (1)

are integrated together with one equation for the rotation of the ray centered coordinates and the kinematic ray tracing equations in spherical coordinates.

The standard linear system of dynamic ray tracing equations can be derived from the non-linear system above if paraxial approximations are substituted. These substitutions assume q_i is small with respect to the scale length v/v_i of the medium, estimate h equal to 1, and calculate V_1 and V_2 by the first two terms of a Taylor expansion about the central ray (Kim and Cormier, 1990; Cerveny, 1985).

In this application, the primary advantage of the vicinity ray tracing equations is that amplitudes and wavefront curvature are calculated from differential equations having terms that depend on only the first spatial derivatives of velocity. Standard dynamic ray tracing requires calculation of second spatial derivatives of velocity in ray centered coordinates, involving multiple transformations between second spatial derivatives specified in ray centered, spherical, and Cartesian coordinates. While straightforward, these transformations represent significant algebraic effort in a model specified in spherical coordinates. Another advantage of the vicinity ray tracing system is that unlike standard dynamic ray tracing, in which jump conditions must be satisfied on elements of the \mathbf{Q} and \mathbf{P} matrices at discontinuities in velocity gradient, no jump conditions are

needed on (q_1, q_2) and (η_1, η_2) . Equations (1) are simply continued across first and second order discontinuities using Snell's law.

After integrating equations (1), the geometric spreading factor is calculated by

$$R = \sqrt{\frac{q_1 q_2}{\tan \eta_1 \tan \eta_2}}$$

(2)

$\pi/2$ phase changes are tracked along the reference ray by counting the number of sign changes in q_1 and q_2 as equations (1) are integrated. The amplitude of a body wave at any point along the reference ray is proportional to $1/R$. In the examples discussed in the following sections, amplitudes and travel times are displayed as contoured residual spheres (Creager and Jordan, 1984) of travel times and amplitudes anomalies computed in a reference radially symmetric model PREM (Dziewonski and Anderson, 1981) and PREM perturbed by a slab structure. The travel time residuals are computed from $T_0 - T_S$ and the amplitude residuals from $\log_{10} A_0 - \log_{10} A_S$, where the subscript o denotes the result for the reference model and the subscript S denotes the result for the perturbed model.

Slab parameterization. Most of the slab velocity models are derived from thermal models specified on two-dimensional

grids. The two-dimensional Cartesian grids are converted to a polar grids using a transformation between angular θ and horizontal X distance, $\theta = X/r$ where r is the radius corresponding to the mid-depth point of the thermal model. The thermal models are next converted to velocity models by assuming a temperature derivative of velocity. All models extend $\pm 5^\circ$ along strike from the assumed source position. The slab models are added as perturbations to a radially symmetric model, taken to be the 1 Hz. isotropic PREM (Dziewonski and Anderson, 1981). Within the slab, the fractional perturbation of S velocity from its value in the surrounding mantle is observed to be more than twice the fractional perturbation of P velocity, or $\delta\beta/\beta \geq 2 \delta\alpha/\alpha$. For values of $\delta\ln\beta/\delta\ln\alpha \geq \alpha/\beta$ (about 1.7 in the mantle) perturbations of ray paths will be larger for S waves than P waves, and the effects of slab structure are expected to be larger on S than on P waves. Hence, many studies, including the one presented in this paper, concentrate on modeling slab effects on shear waves.

Focusing and Defocusing Experiments

Slab Distortion Below 650 km Depth?

Vicinity ray tracing was performed for a series of different slab models derived from thermal models with varying source

locations and a temperature derivatives of S velocity, $d\beta/dT = 0.65 \text{ m s}^{-1} \text{ K}^{-1}$. The first two models considered were derived from P velocity models proposed by Creager and Jordan (1986) and Fischer et al. (1988) for the Kuril-Kamchatka slab. For this slab, Fischer et al. examined the tradeoffs in slab width, penetration, and velocity perturbation below 650 km depth consistent with P travel time residuals. Figure 3 shows the form of the two models, A and B, which cannot be distinguished at similar high confidence levels by travel time inversion. Model A, which remains thin below 650 km depth, was slightly better than Model B in reducing the variance calculated from difference between observed and predicted P residuals.

Figure 4 compares the S and ScS travel time residuals derived from the P wave models under the assumption that $d\beta/dT = 0.65 \text{ m s}^{-1} \text{ K}^{-1}$. These travel time residuals, as well as all others shown in this paper, have a mean value averaged over area added to the true residual pattern, which is uniformly negative. The addition of the mean value or choice of a zero baseline is designed to mimic the processes of residual sphere smoothing and correction for an unknown origin time described in Creager and Jordan (1984). Although significantly larger negative anomalies in S and ScS travel time are observed in the model B, which thickens below 650 km depth, it might be difficult to distinguish between A and B using P data having a 3.5 factor smaller gain in anomaly.

The smallest P anomalies would be swamped by noise in the data, and it would require a dense azimuthal coverage in regions having the strongest anomalies to discriminate between the two models. Both models A and B predict maximum anomalies in ScS travel times roughly consistent with those first reported by Jordan (1977). Model B appears to be in slightly better agreement with Jordan's (1977) ScS data for the Kuril-Kamchatka slab, coming closer to the peak ScS travel time anomalies of about -7 seconds.

Figure 5 compares the S and ScS amplitude anomaly predicted for the two models shown in Figure 3. The amplitude anomalies in Figure 5 correlate with the travel time anomalies in Figure 4 only in a broad regional sense. In model A, the lowest amplitudes and fastest travel times are located on the dipping side of the slab in azimuthal sectors centered about lines at $\pm 15^\circ$ with respect to the strike of the slab. In model B the most intense anomalies are aligned closer to the strike of the slab. The broad sense of the correlation of amplitudes and travel times in these regions agrees with the expectation that a high velocity region such as a descending slab will defocus body waves. The lowest amplitude anomaly of model A is -0.9 and the minimum travel time anomaly is -5 seconds; for model B it is -0.8 in amplitude and -10 seconds in travel time anomaly. In both models, the minimum amplitude anomaly is displaced in position from the minimum travel time anomaly. Note, for

example, that the minimum amplitude anomaly in model B will occur at 40 to 50 great circle degrees at azimuths close to the strike of the slab, whereas the minimum travel time anomaly will occur around 70 great circle degrees at azimuths displaced slightly toward the side of the slab opposite its dip. At azimuths perpendicular to the strike on the dipping side of the slab, zero and weak positive S amplitude anomalies are associated with weak positive and negative S travel time anomalies. There are thus many local exceptions to the expected rule of fast regions correlating with regions of low amplitude and slow regions correlating with regions of large amplitudes.

These results agree with the results obtained by Weber (1990) in a two-dimensional study of slab focusing and defocusing. They also illustrate that amplitudes can provide constraints independent of travel times in the modeling of slab structure. A similar result has been more rigorously demonstrated in studies that attempt to invert for structure, simultaneously using amplitude and travel time data. Nowack and Lutter (1988) have shown that amplitudes are most sensitive to the edges of a velocity anomaly, while travel times are most sensitive to the center of a velocity anomaly. This effect can be most clearly seen in plots of ray trajectory, in which rays shot at equal take off angles are often seen to concentrate in regions of strong velocity gradient (e.g., Cormier and Spudich, 1984; Cormier, 1987).

From these results, we can expect that amplitude data may be potentially valuable in resolving the boundaries of a slab structure and its total width.

In Figure 5, both A and B models predict large negative amplitude anomalies (defocusing) of S waves observed along the strike of the slab. The regions in which the negative anomaly in log amplitudes is less than -0.5 can be expected to exhibit a significant amount of pulse broadening due to slab diffraction. Model A, which remains thin below 650 km depth, defocuses ScS as well as S along the strike of the slab. Model B, which thickens below 650 km depth, however, defocuses ScS to a much lesser extent. Using Figure 1 to predict slab diffraction effects, one can conclude that model A, which remains thin below 650 km, will broaden the waveform of both S and ScS along strike, whereas model B, which thickens below 650 km, will broaden S but not ScS along strike. The broadening of ScS in model A will cover nearly an entire 180° sector on the dipping side of the slab. The broadening of S in model B will be concentrated in geographic regions along azimuths parallel to the strike of the slab at distances less than about 60° .

Broadband S and ScS waveforms from deep focus Kuril-Kamchatka events can be observed at azimuths along the strike of the slab at seismographic stations in North America (Silver and Chan, 1986). Since in most of the examples collected, it is

S and not ScS that seems to have significantly broader pulse width, these data are most consistent with a Kuril-Kamchatka slab that advectively thickens below 650 km depth.

A similar conclusion was reached in the S waveform studies of Vidale (1987), using a two-dimensional finite difference synthesis method, and by Cormier (1989), using a superposition of Gaussian beams in two and three dimensions. These studies concluded that while some deep slab structure may be present below 650 km depth, an S velocity model of type A, which remains thin below 650 km depth, predicts too large a distortion in the waveforms of S waves at take-off angles corresponding to ScS and SKS. In our present study, assuming the correctness of the hypothesis that strong amplitude anomalies are associated with pulse broadening, a slightly stronger conclusion can be made. Not only is Model A inconsistent with the observed S waveform data, but features of Model B, having some advective thickening below 650 km depth, may begin to predict some of the trends seen in the data, i.e., the strongest pulse broadening is observed along strike in S waves at distances equal to or less than 55 degrees (Figure 6).

Gaherty et al. (1989) have compared SH and ScSH amplitude and travel time residuals for several deep focus earthquakes occurring in the Kuril-Kamchatka slab. A signature of slab structure in their data can primarily be seen in azimuths

along strike. When compared with predicted amplitude anomalies, the observed amplitude anomalies seem to be more consistent with a slab that has grown in width below 650 km depth than one that has remained thin below that depth. A thin deeply penetrating slab predicts much stronger than observed amplitude and travel time anomalies along azimuths perpendicular to the strike in the down dip direction.

*Effect of a Discontinuous Increase in Mantle Viscosity at
650 km Depth*

The two slab models just discussed have been based on thermal models that do not account for variations in the viscosity of the mantle and the temperature dependence of viscosity. Advective thickening was introduced in an ad hoc fashion to investigate the range of possible models consistent with travel time anomalies.

Gurnis and Hager (1988) have computed a thermal model that includes the effects of a lower mantle having a factor of 30 increase in viscosity. The effect of the viscosity increase is to induce advective thickening in the thermal structure and a pronounced broadening of the slab velocity anomaly below 650 km depth, with much a much weaker thermal anomaly

and inferred velocity anomalies below 650 km than in Model B (Figure 7).

The predicted amplitude and travel time anomalies of S and ScS waves for a 540 km deep earthquake are shown in Figure 8. Measurable travel time and amplitude anomalies are seen primarily in the S waves and less so in ScS waves for deep focus sources. The gain in the travel time anomalies is roughly equivalent to that of Model A for the Kuril-Kamchatka slab, but the gain in amplitude anomalies is much weaker than either models A and B and the location of the peak anomalies in both travel time and amplitude has been shifted to shorter distance ranges in S. Using the waveforms shown in Figure 1 to calibrate the amplitude and anomalies for waveform broadening, it is predicted that the Gurnis and Hager model will not produce much waveform distortion in either the S or ScS waves of deep focus earthquakes, except possibly in S waves at ranges between 40 to 60 degrees at azimuths 10 to 30 degrees from the strike of the slab on dipping side of the slab.

Comparison of the amplitude anomalies shown in Figure 8 with the pulse broadening data shown in Figures 6 suggests that model B is a better model for the Kuril-Kamchatka slab. Even if the dip of the Gurnis and Hager model were steepened to be consistent with the dip of the Benioff zone defining the Kuril-Kamchatka slab, it would produce too small of an

amplitude anomaly in S to be consistent with the waveform broadening observed reported by Silver and Chan (1986) at azimuths along the strike of the slab. The intensity of travel time anomalies in ScS observed from deep focus events in the Kuril-Kamchatka slab (Jordan, 1977) is also more consistent with the stronger intensity of S velocity anomaly below 650 km depth shown in Figure 3b.

Variations in Source Position

With the best data available for hypocentral location, including travel times from local arrays above the earthquake and/or calibration of local structure from a master event, it is never possible to locate the hypocenter of a deep focus event to any accuracy better than about ± 10 km. In practice, this lower limit is also set by the characteristic source dimension of the $m_b = 5.5$ to 6 of deep focus earthquakes most commonly studied at teleseismic range. It is generally unknown whether most of the energy observed in a body wave or teleseismic range is radiated at or near the point at which rupture initiated or stopped. Although it may be reasonable to assume that rupture initiates in the highest velocity core of the slab, this is as yet an unproved assumption. For these reasons, it is important to investigate the effect of source position within a slab on the pattern of amplitude and travel time anomalies.

The amplitudes and travel times of S and ScS waves were calculated for a SH point source located at positions I to V in the slab model shown in Figure 9. Figure 10 shows the resultant travel time and amplitude anomaly patterns for lateral positions I and II.

The results of these tests can be summarized as follows:

1. *Lateral position fixed and depth varied.* Amplitudes and travel times smoothly change, with anomalies decreasing in amplitude as source depth increases.
2. *Fixed source position and temperature derivative of velocity varied.* Amplitudes and travel times smoothly change, with anomalies decreasing in magnitude as temperature derivative of velocity decreases.
3. *Depth fixed and lateral position varied.* For changes in lateral position up to 50 km, broad regional anomalies in amplitude and travel times change by a small amount, but transitions between low and high amplitudes or between fast and slow times change dramatically in location and intensity. Figure 11 compares the end points of S rays for source positions I and II, showing that multipathing and caustics are easily induced when the lateral location is near a rapid change in velocity gradient. There are some features in the anomaly pattern that are relatively stable for changes in

lateral source position, e.g., the broad anomaly in S waves in the down dip direction at azimuths close to the strike of the slab and the strong anomalies in ScS everywhere on the dipping side of the slab.

For purposes of using amplitudes to model slab structure, the most important of these is the third result. The broad amplitude low and travel time minimum in S waves on the down dip side of the of the slab at azimuths close to the strike and the strong anomalies in ScS everywhere on the dipping side of the slab are the most stable features of the anomaly pattern of a thin, deeply penetrating slab. These features are relatively insensitive to changes in source position up to 50 km vertically or laterally. Their presence or absence and their intensity strongly constrain the slab structure below the hypocenter. If the intensity of the amplitude anomaly is less than -0.5 in log amplitude units than it is likely also to be associated with a secondary, slab diffracted pulse and/or broadening. If strong amplitude and/or waveform anomalies are absent in ScS but are present in S primarily along azimuths close to the strike of the slab, then such an observation would suggest slab penetration below below the hypocenter but with some distortion and advective thickening.

Bent Slabs and Multipathing

Multipathing in three-dimensional structure, as in two-dimensional structure, is usually associated with the development of caustic surfaces and Hilbert transformation of ray paths that touch the caustic surfaces. Silver and Chan (1986) suggested that multipathing may be responsible for the pulse broadening observed in some of the broad band S waveforms they observed from deep focus events. To explain the observed waveforms, the multipathing must be such that the interfering multiples produce displacement pulses that do not change polarity throughout the summed waveforms of the multiples. Since the $\pi/2$ phase shift of the Hilbert transformation produces time segments of both positive and negative polarities, the multipathing scenarios proposed by Silver and Chan were investigated to see if they can produce broadened displacement waveforms of constant apparent polarity.

Silver and Chan found that bent slabs such as that shown in Figure 12 can produce multipathing in several different azimuthal regions for sources that lie in the region above the bend. Figure 13 shows that two types of azimuthal regions will exhibit multipathing. Figure 14 shows waveforms predicted from vicinity ray tracing to receivers

lying in these regions. The synthetics incorporate the relative geometric spreading of each multipath, multipath interference, and the $\pi/2$ phase shifts of Hilbert transformed paths. The waveforms at receiver locations A, B, C, and D lie in a region of strong focusing, while the waveforms at receiver locations F and E lie in a region that is relatively defocused. Only the waveform at position D bears any resemblance to the type of pulse broadening seen in the data discussed by Silver and Chan. While this type of multipathing may often exist in the case of hypocenters lying above a bend in the slab, it is unlikely to produce the type of pulse broadening over a sufficiently broad geographic area seen in S waveforms. When multipathing does exist, the resultant displacement waveforms will more often exhibit a segment of reversed polarity. These results confirm those obtained from waveform modeling that includes frequency dependent diffraction (Vidale, 1987; Cormier, 1989; Engdahl et al., 1989), i.e., slab diffraction can produce broadened and complex waveforms having uniform displacement polarity over a broad azimuthal range. Slab diffraction need not be associated with multipathing, although it may smoothly grade into a region of ray theoretical multipathing as azimuth and/or distance changes.

Conclusions

In a series of experiments using a modified form of dynamic ray tracing, we have shown that S wave amplitudes in conjunction with S travel times can provide important constraints on the slab structure below the cutoff in seismicity. In interpreting the amplitude anomaly patterns, we have assumed that the regions of strongest defocusing are coincident with regions in which significant pulse broadening due slab diffraction occurs. This assumption is based on the correlation of defocusing and pulse broadening seen in methods that include the frequency dependent effect of slab diffraction. Thus, some of the specific conclusions about the behavior of pulse broadening below should be accepted with caution until verified by numerical modeling of frequency dependent slab effects in three-dimensional models.

Correlation of Amplitudes with Travel Times

The focusing and defocusing effects of slab structure act to produce only a weak correlation of amplitude with travel time. Amplitudes correlate with travel times only in a broad regional sense: high amplitudes with slow times and low amplitudes with fast times. Localized intense amplitude anomalies do not correlate with localized intense travel time

anomalies. Ray tracing experiments show that this behavior is consistent with amplitudes being most sensitive to the edges of a velocity anomaly, while travel times are most sensitive to the center of a velocity anomaly.

Use of Waveforms and Amplitudes in Modeling Slab Structure.

Waveforms and amplitudes provide independent constraints in the modeling of slab structure. The relative broadening and amplitude anomalies of direct S versus those of S waves having steep vertical take-off angles, such as ScS and SKS, are particularly valuable in discriminating between different slab structures below 650 km depth. Although waveforms, amplitudes, and travel times vary most rapidly in the azimuthal region surrounding the strike of the slab, a dense sample of S and ScS waveforms in this region can provide powerful constraints on deep slab structure. Waveform broadening in S but not ScS from deep focus earthquakes observed along the strike of the slab, for example, is consistent with advective thickening and slab distortion below 650 km depth.

The Kuril-Kamchatka Slab

Strong negative anomalies in the travel times of ScS waves at azimuths on the dipping side of the slab and waveform

broadening in S waves at azimuths along the strike of the slab from the deepest focus earthquakes strongly argue for some type of slab structure or thermal anomaly below 650 km depth. Thin, deeply penetrating slabs, however, produce strong signatures in the amplitudes and waveforms of ScS, SKS, and SKKS in a broad azimuthal range on the dipping side of the slab that are not observed in data. Waveform broadening in S but not ScS at ranges less than 60° at stations along the strike of the slab suggests either a decrease in the temperature contrast of the slab, a decrease in the temperature derivative of S velocity ($d\beta/dT$) and/or some advective thickening or distortion below 650 km depth. A model of the Kuril-Kamchatka data most consistent with all data is one in which a slab structure exists below 650 km depth, but with a factor two to three advective thickening over the deep slab models originally proposed by Creager and Jordan (1986).

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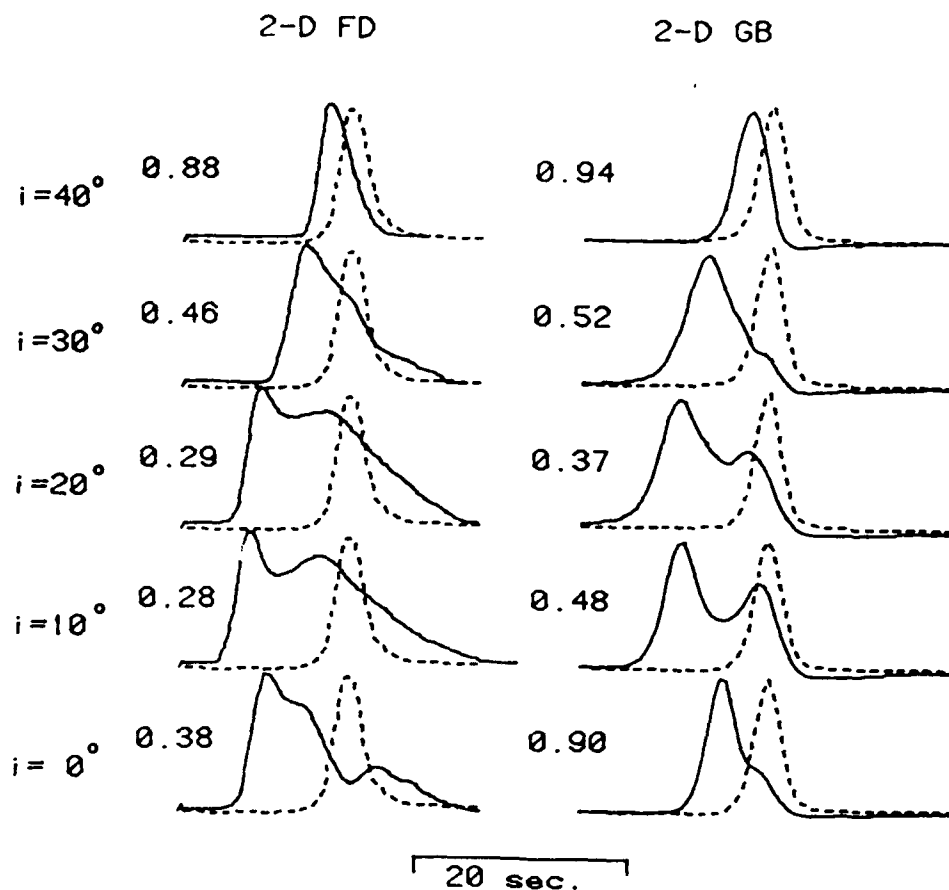


Figure 1. SH waves radiated by a deep focus point source in a slab model synthesized by the two-dimensional a finite difference calculation (Vidale, 1987) and a three-dimensional superposition of Gaussian beams shot reciprocally from receiver to source (Cormier, 1989). The dashed traces are reference waveforms for PREM patched to a homogeneous halfspace at 1400 km depth. Numbers to the left of each trace give the ratio of the peak amplitude of the seismograms synthesized in the slab structure to the peak amplitude of the reference waveforms.

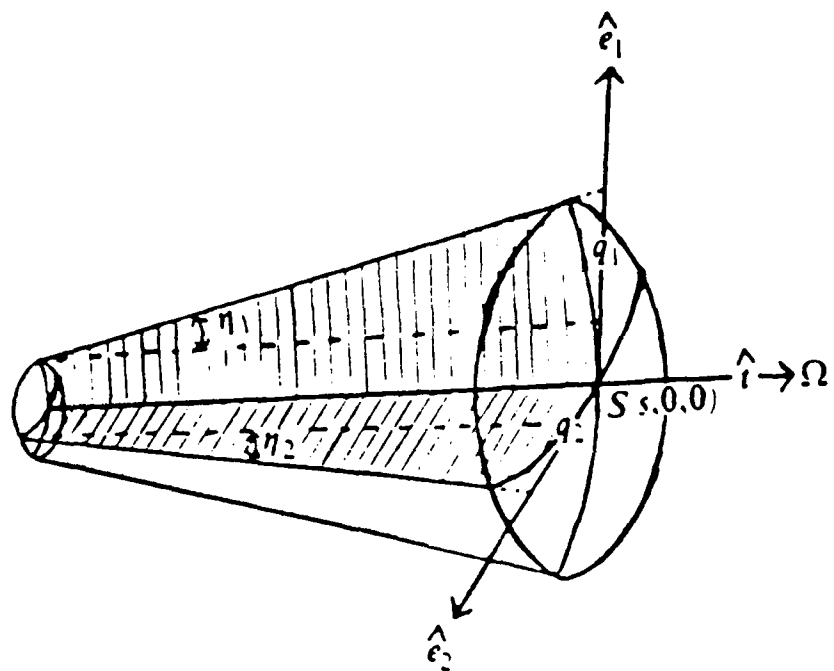
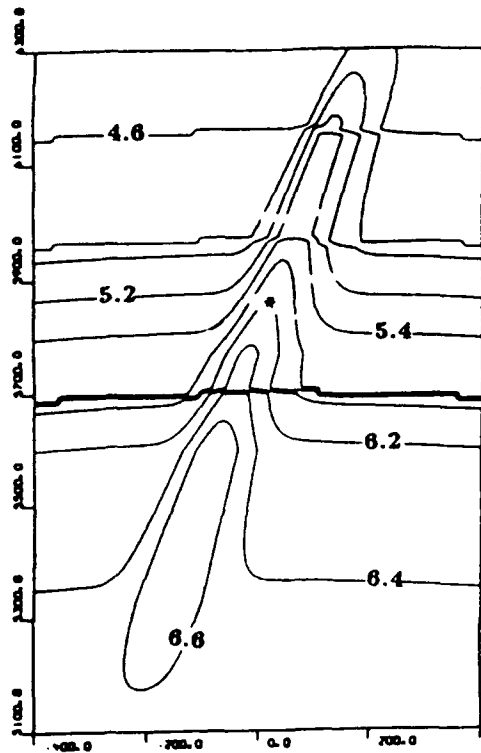


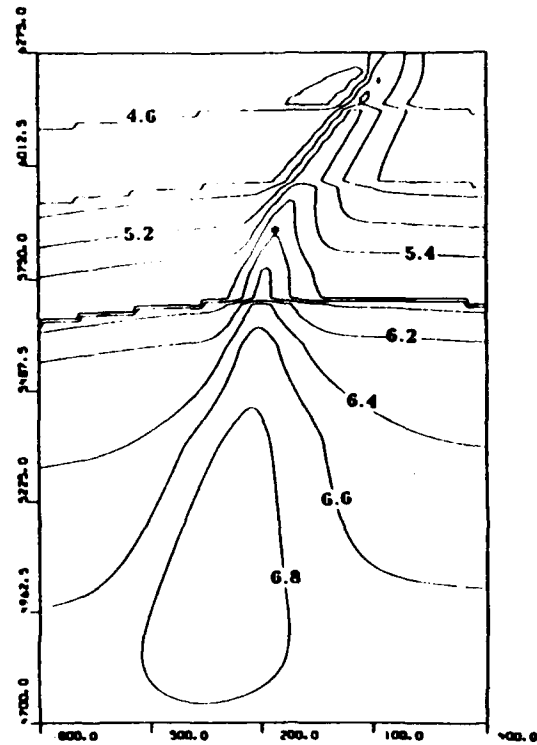
Figure 2. Geometry and definition of the quantities η_i and q_i in the vicinity ray tracing system.

I. Narrow Slab Below 650 km. -- Kurils



(a)

II. Wide Slab Below 650 km. -- Kurils



(b)

Figure 3. S wave models of the Kuril-Kamchatka slab based on thermal models determined from P wave travel time anomalies in studies by (a) Creager and Jordan (1986) and (b) Fischer et al. (1988). Model (b) is the end member of a series of models consistent with the data having the greatest amount of advective thickening beneath 650 km.

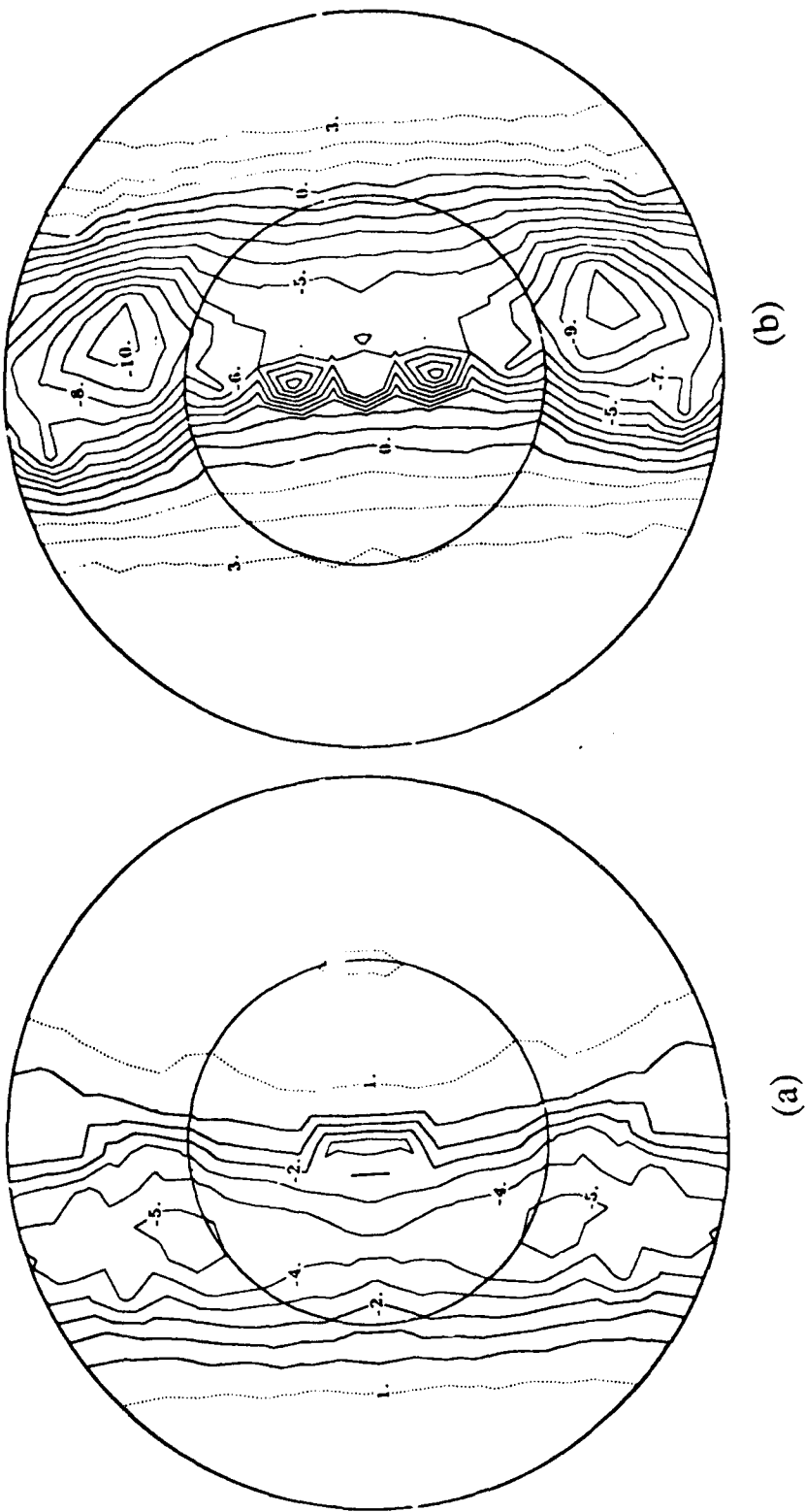
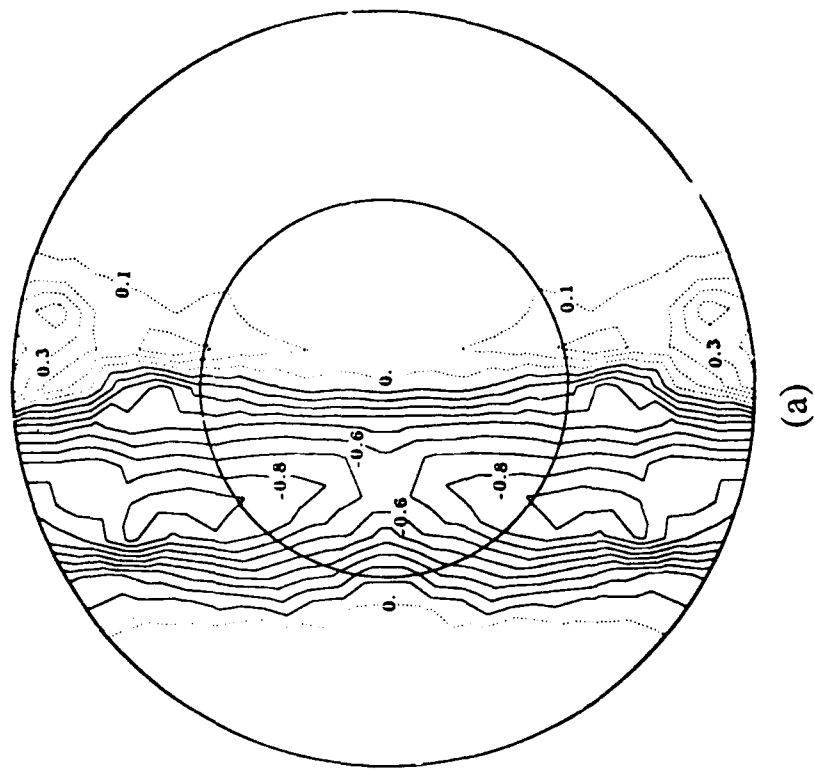
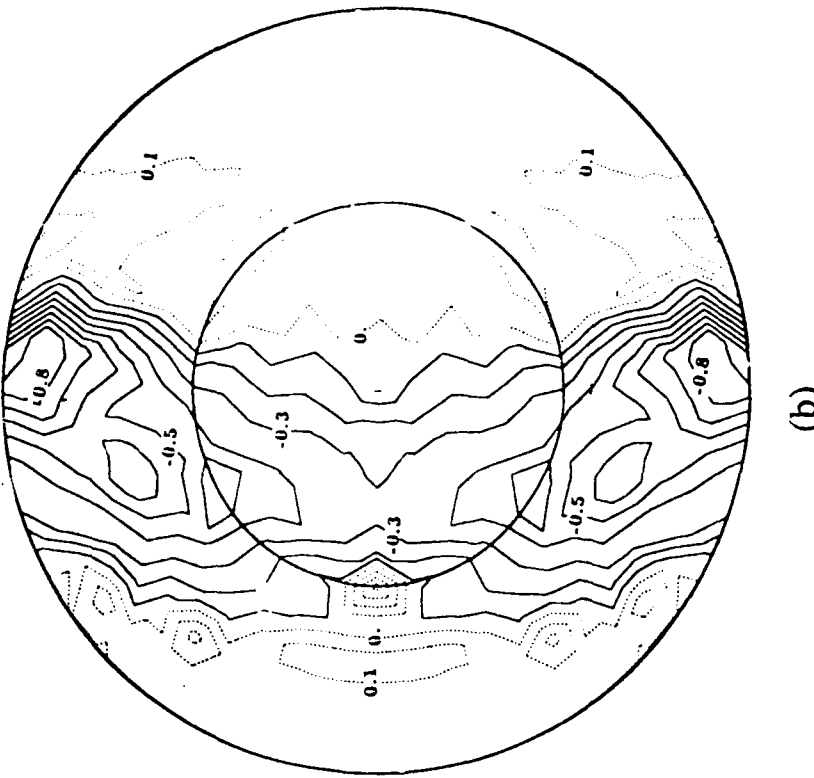


Figure 4. Comparison of travel time anomalies in slab models (a) and (b) shown in Figure 3.



(a)



(b)

Figure 5. Comparison of amplitude anomalies in slab models (a) and (b) shown in Figure 3.

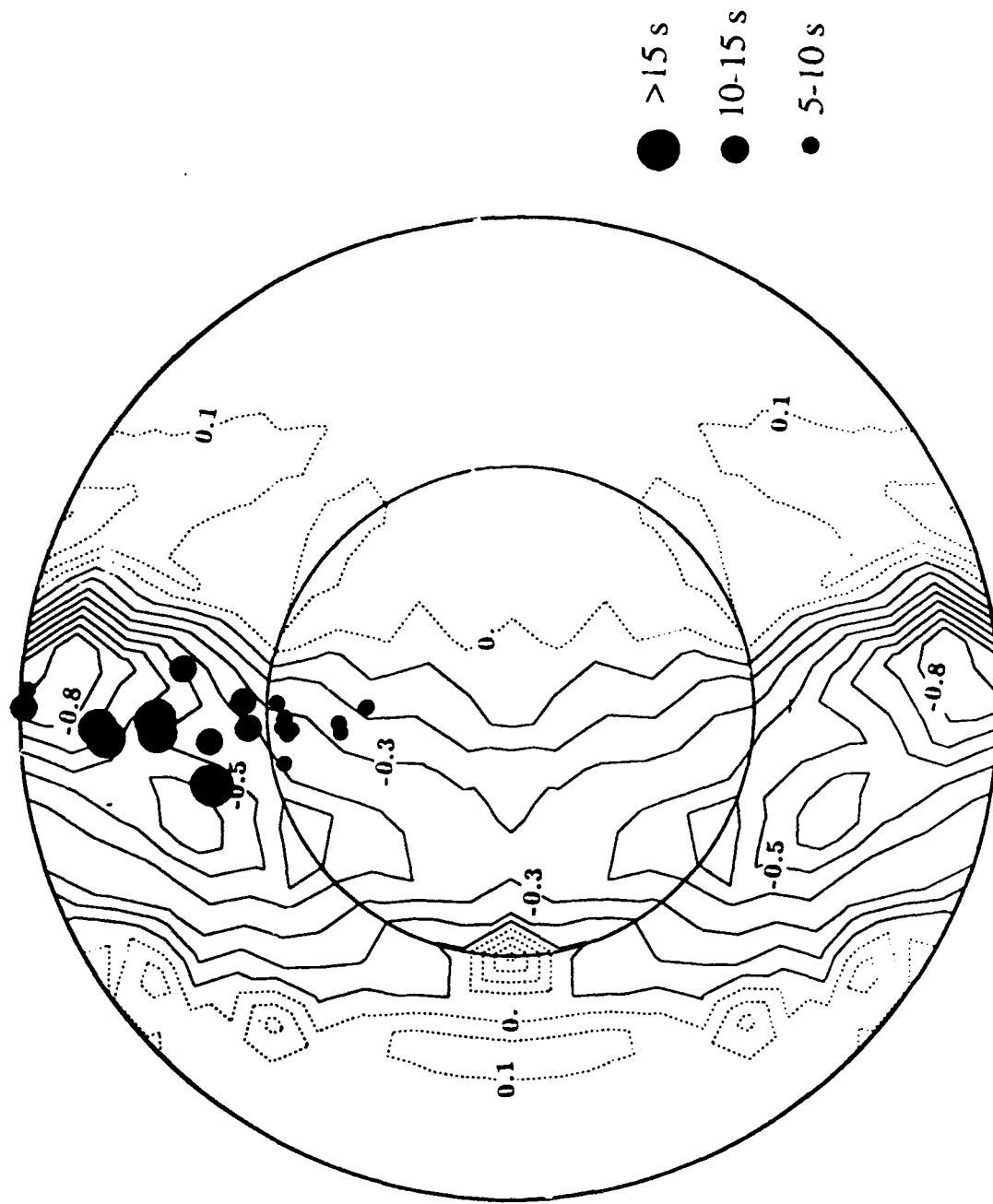


Figure 6. Pulse broadening of S and ScS in seconds calculated by Silver and Chan (1986) from two deep focus earthquakes in the Kuril-Kamchatka slab. Pulse broadening anomalies are plotted in the contoured residual spheres of peak amplitude anomalies of slab model (b) of Fischer et al. (1988).

**Wide Slab Below 650 km.
(Effect of Viscosity Increase at 650 km.)**

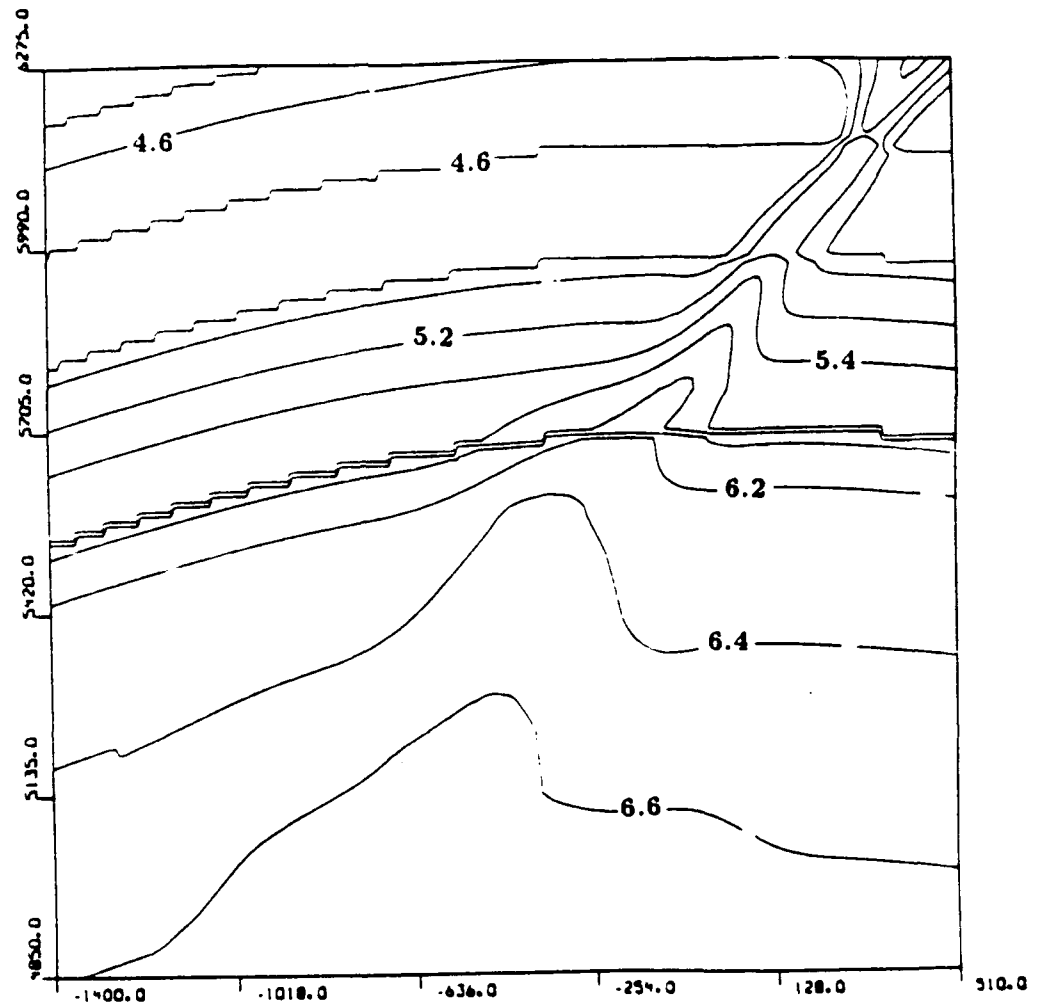
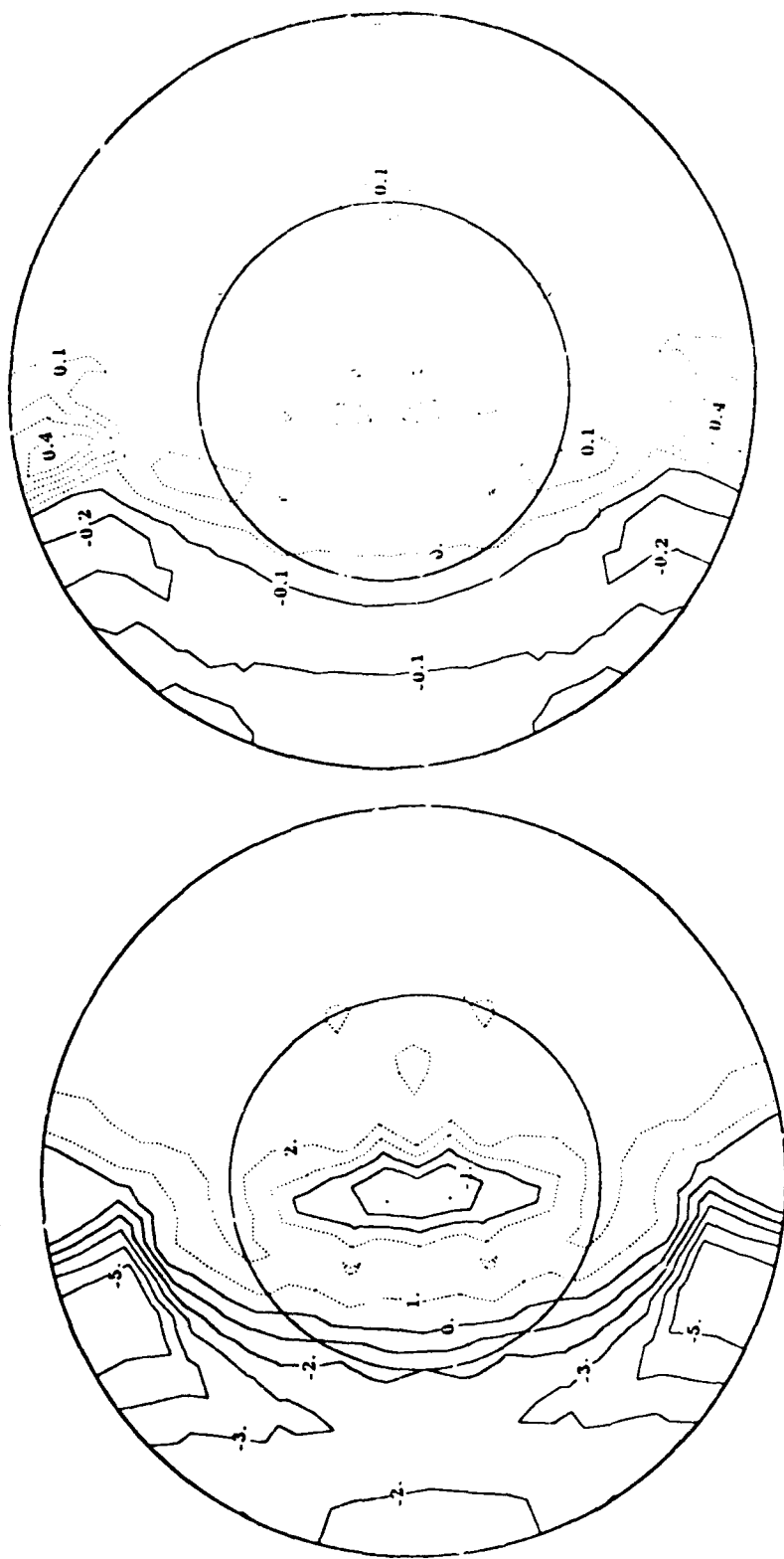


Figure 7. Slab model for S velocity determined from the thermal model of Gurnis and Hager (1988) for a slab encountering a factor 30 increase in viscosity at 650 km depth.



GURNIS AND HAGER MODEL

S Travel Time Anomalies

S Amplitude Anomalies

Figure 8. Travel time and amplitude anomalies computed for the slab model shown in Figure 7.

Effect of Source Location

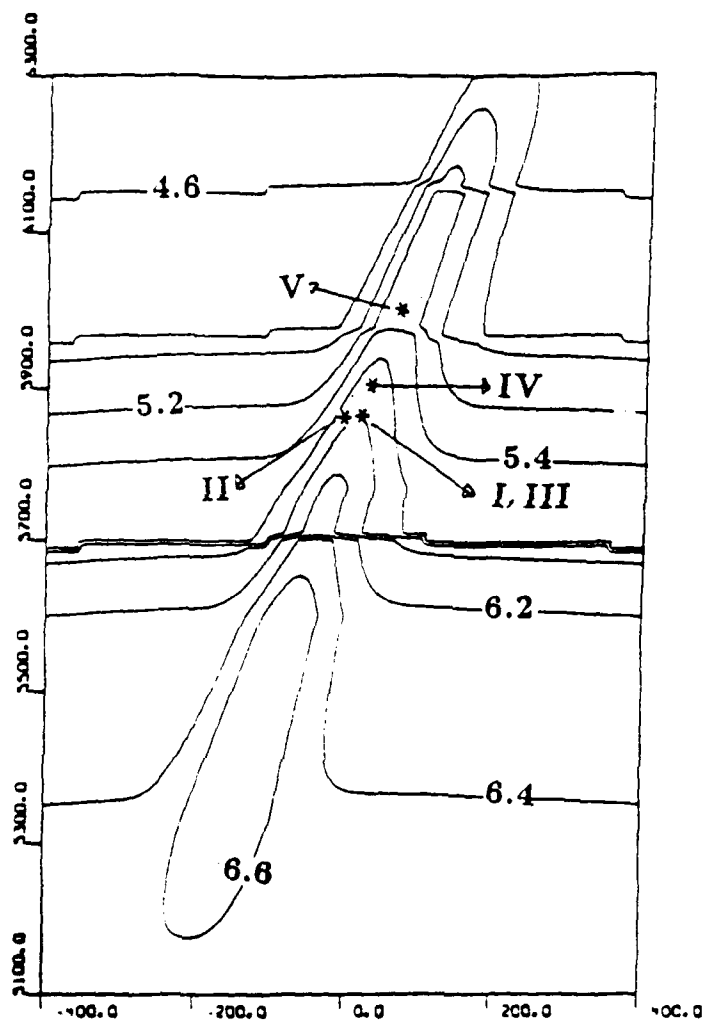
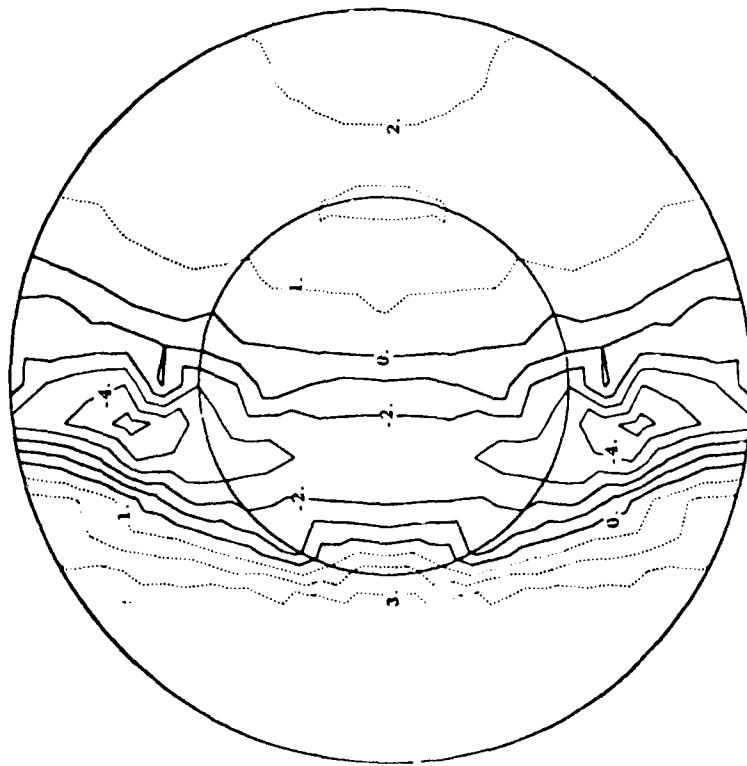
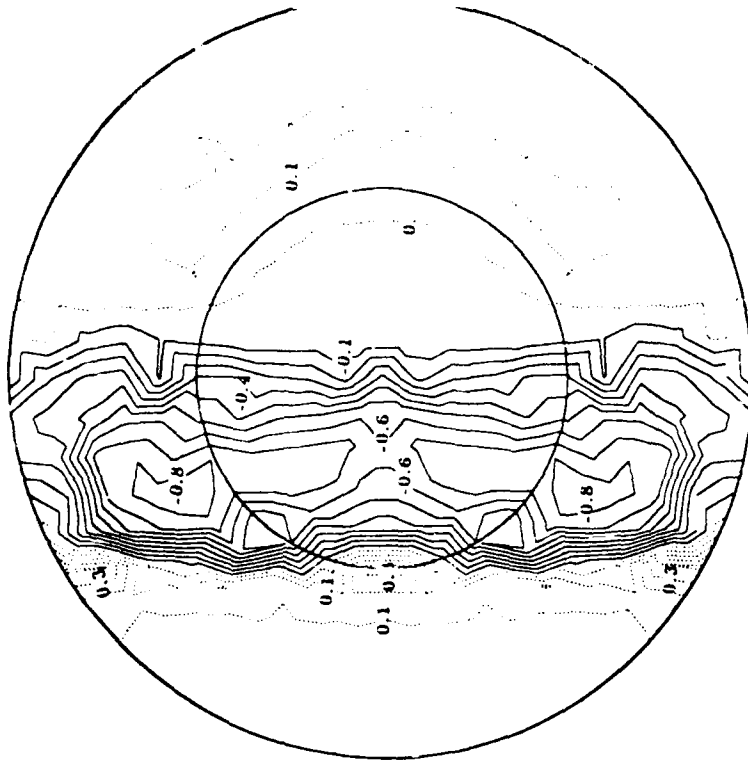


Figure 9. Source positions used in experiments to determine the effects of unknown source position on amplitude anomalies.



S Travel Time Anomalies



S Amplitude Anomalies

Figure 10. Travel time and amplitude anomalies for a shift in lateral source position toward the region of high velocity gradient defining the upper surface of the slab. These can be compared with the anomalies computed for a source position in the center of the high velocity core in Figures 4a and 5a.

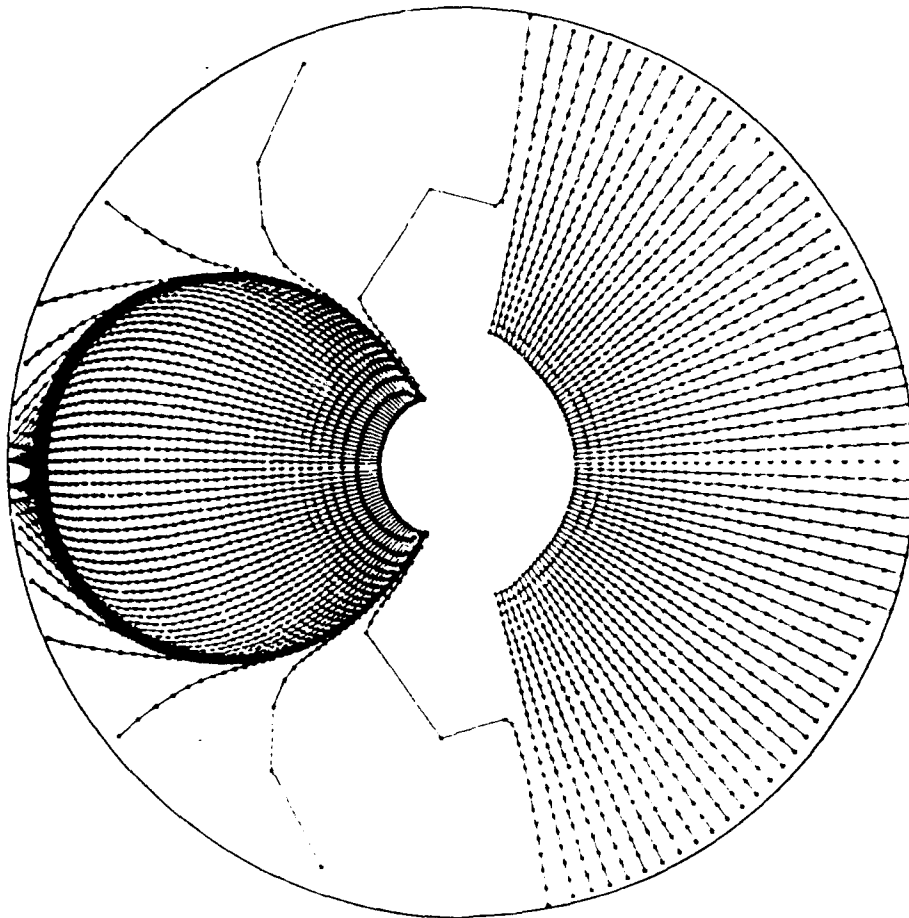


Figure 11. Ray end points projected onto an equal area geographic map for SH waves radiated by the laterally shifted source position II shown in Figure 9. End points are connected for constant azimuthal take-off angles and variable vertical take-off angle.

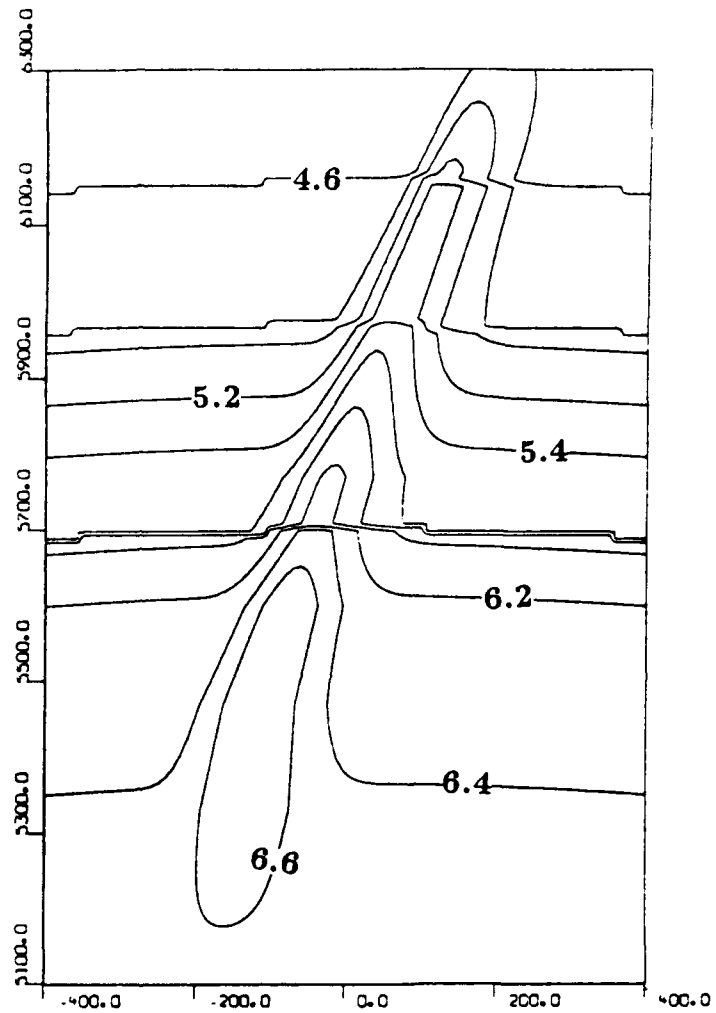


Figure 12. A bent slab model of the type considered by Silver and Chan (1986) for the Kuril-Kamchatka slab. Amplitudes, travel times, and SH waveforms are calculated for the source location shown.

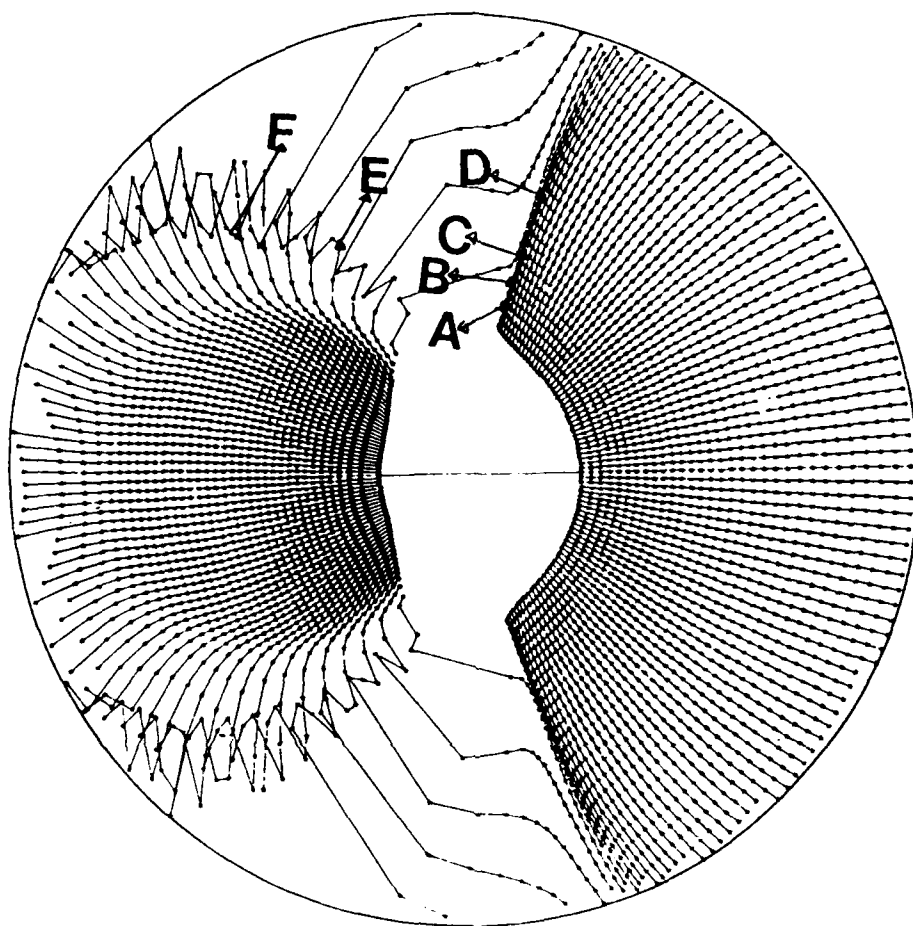


Figure 13. Ray end points projected onto an equal area geographic map for SH waves radiated by the source located as shown in Figure 12. End points are connected for constant azimuthal take-off angles and variable vertical take-off angle, illustrating two types of multipathing. Seismograms were synthesized at geographic locations A - D by summing pulses from each multipath, including effects of the Hilbert transformation.

SH-Synthetic Seismograms for Example X

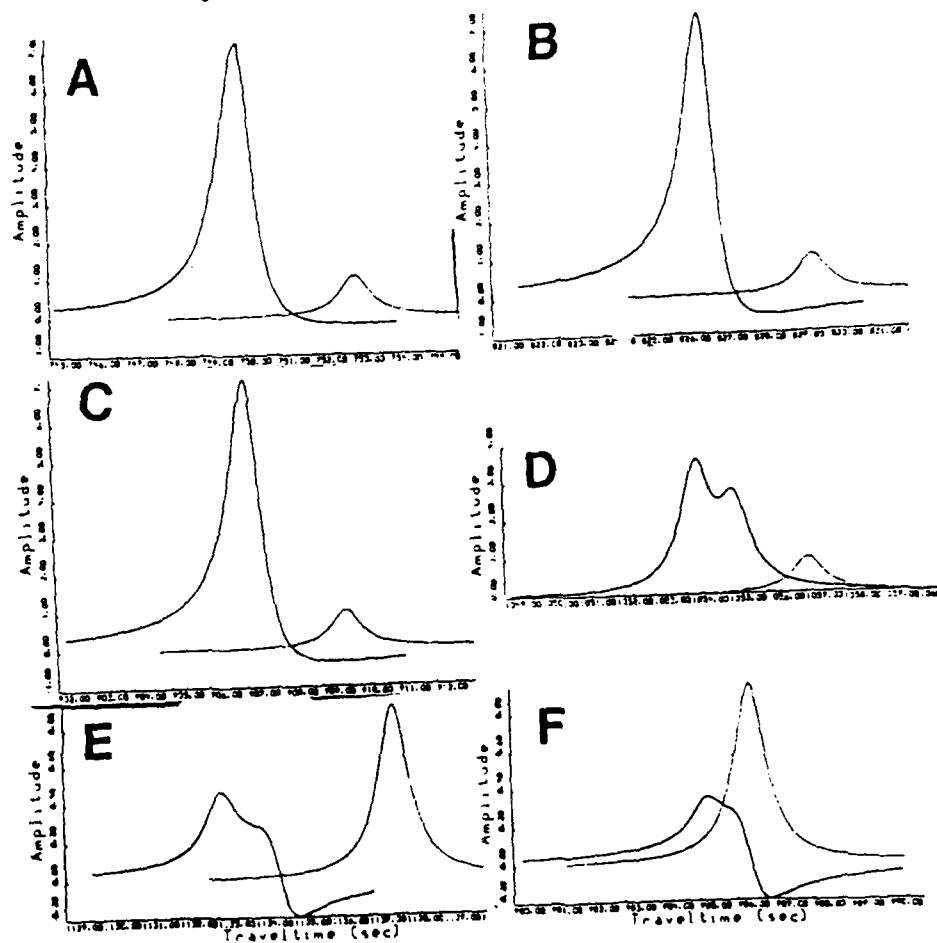


Figure 14. Synthetic SH waveforms at locations A-D shown in Figure 13. Source radiation pattern is assumed constant and effects of intrinsic attenuation are not included.

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